National Aeronautics and
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ARSET
Applied Remote Sensing Training
http://arset.gsfc.nasa.gov
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NASA Trace Gas Products for Air Quality Applications

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Satellite Remote Sensing of Air Quality: Data, Tools, and Applications

Tuesday, May 23, 2017 – Friday, May 26, 2017
Indian Institute of Tropical Meteorology, Pune, India

Satellite Remote Sensing of Trace Gases for Air Quality in a Nutshell

- **Surface Monitoring**
  - Compared to aerosol instrumentation, satellite trace gas instrumentation is generally **not as sensitive** to surface pollution
  - Exceptions: nitrogen dioxide and sulfur dioxide

- **Emissions Inventories and Modeling**
  - Trace gas observations from space have been useful for constraining emissions inventories

- **Vertical Profile Information in the Free Troposphere**
  - Also available for some products (e.g. CO) and derived using the pressure dependence of spectral bands

Satellite Remote Sensing of Trace Gases for Air Quality in a Nutshell

- **Nitrogen Dioxide**
  - Good sensitivity in the planetary boundary layer (PBL)
  - Fire smoke, industrial and transportation sources, stationary sources, top-down emissions inventories

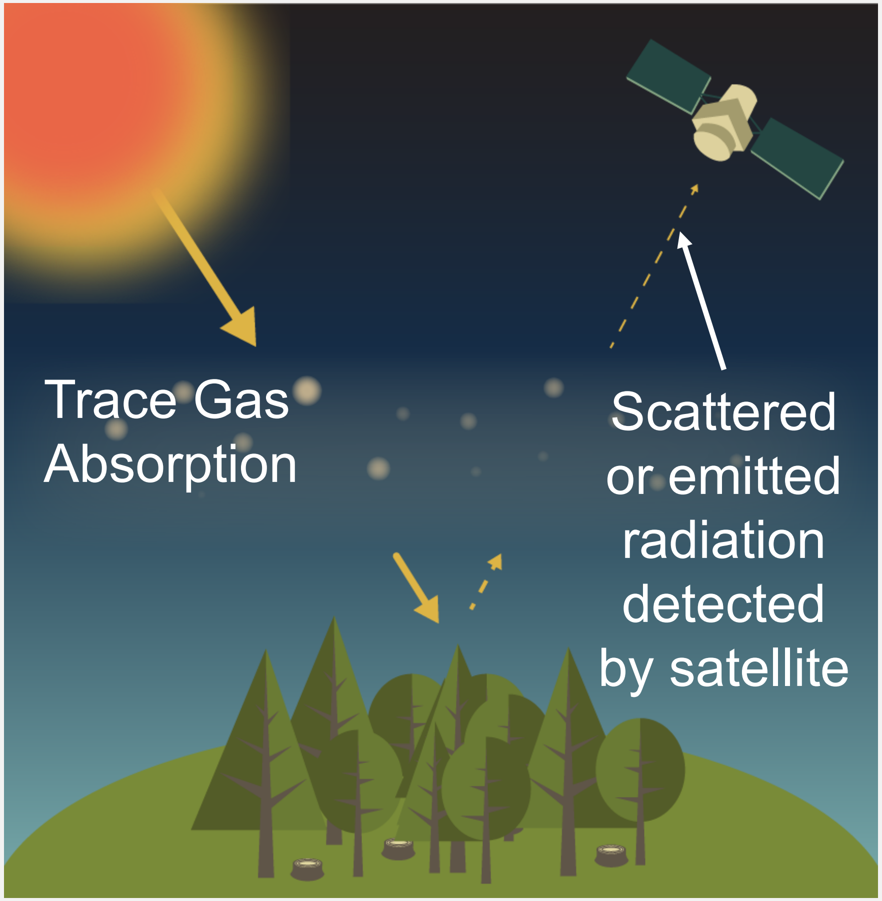
- **Sulfur Dioxide, Ozone, and Formaldehyde**
  - Limited sensitivity in the PBL
  - Sensitive to large point sources, such as electrical generating units and volcanoes

Satellite Remote Sensing of Trace Gases for Air Quality in a Nutshell

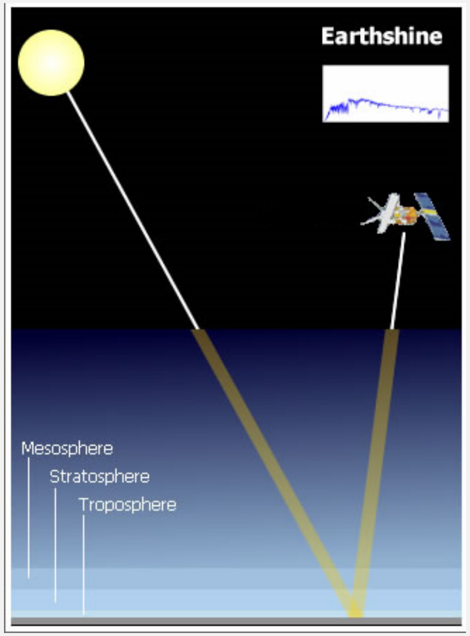
- Carbon Monoxide
  - Good mid-tropospheric sensitivity
  - Useful for monitoring long-range transport of smoke
- Carbon Dioxide and Methane
  - Low spatial resolution
  - Captures global trends

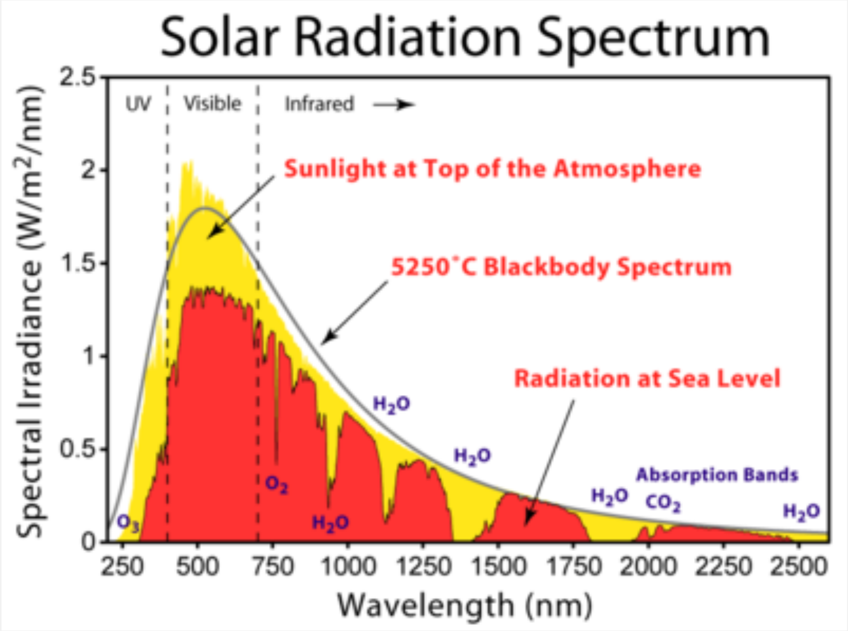
Measuring Trace Gases from Space

- Detect backscattered and/or emitted thermal radiation
- We know the distinct absorption spectra of each trace gas
- We can identify a “fingerprint” for each atmospheric constituent
- Retrieval algorithms (a model) infer physical quantities such as number density, partial pressure, and column amount



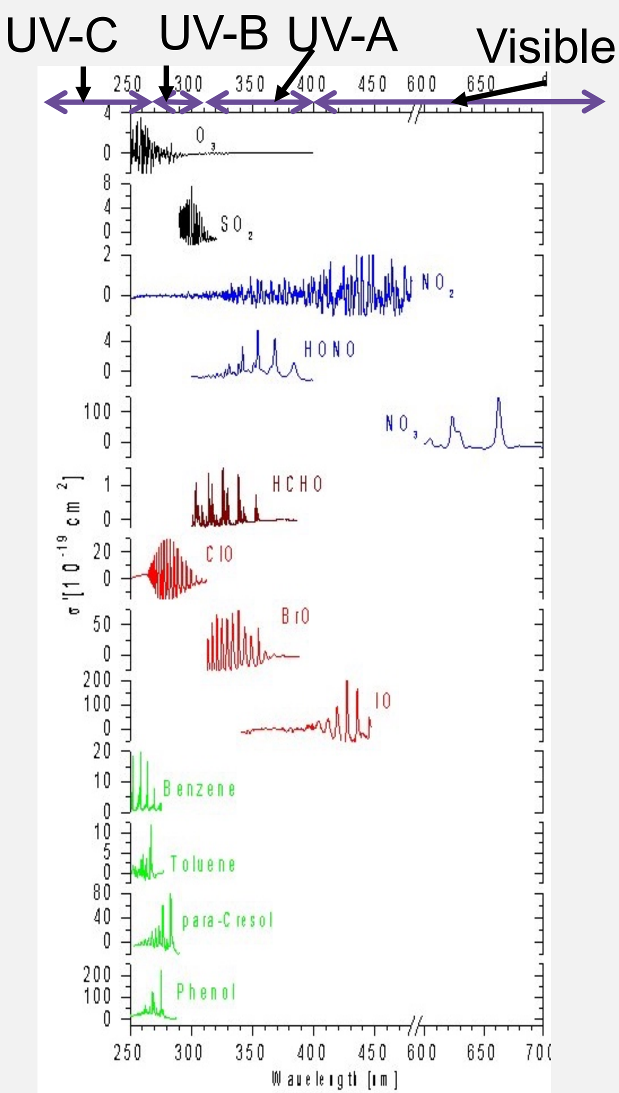
How Satellites Measure Trace Gases

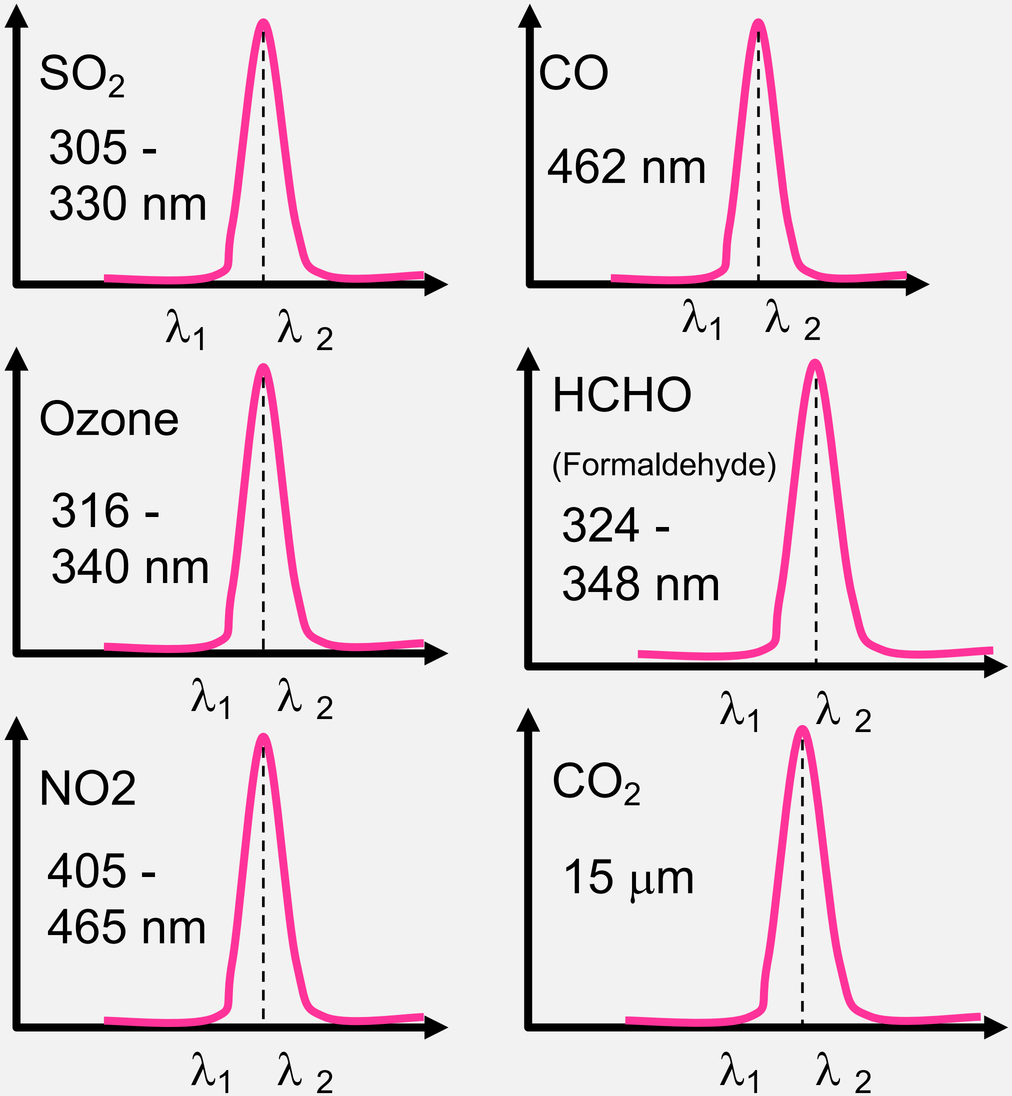




- Trace gases use the signature of gas absorption
- All satellite remote sensing measurements of the troposphere are based on the use of electromagnetic radiation and its interaction with constituents in the atmosphere

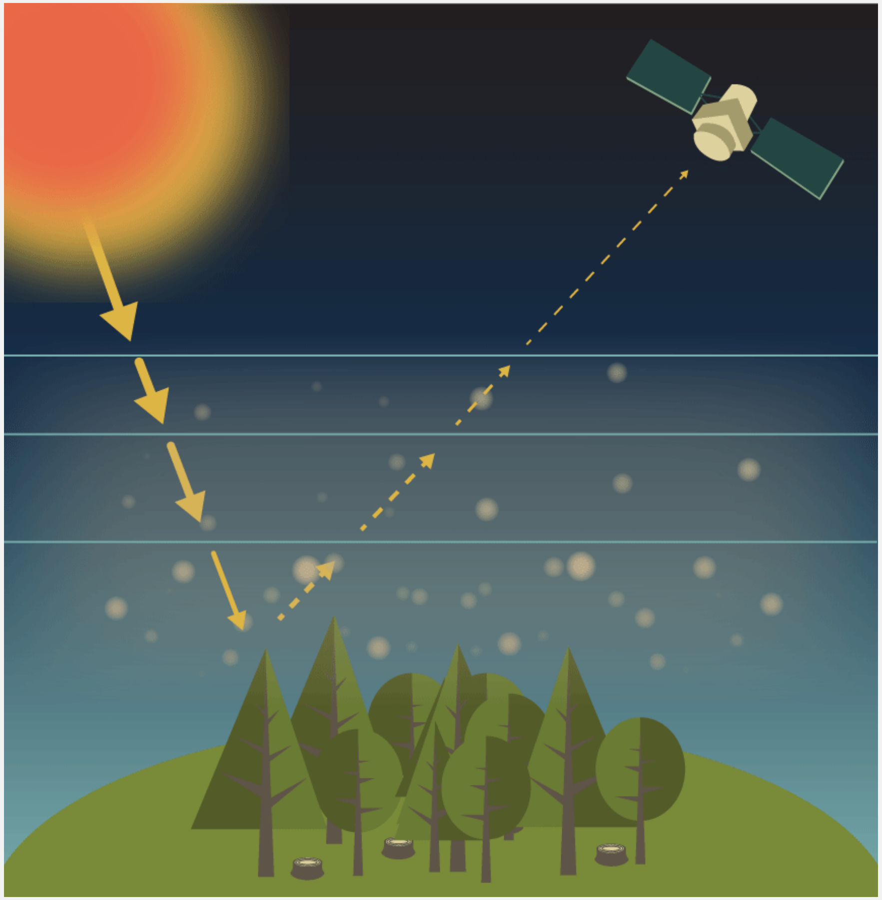
Satellite Measurements Take Advantage of Distinct Absorption Spectra





Vertical Distribution of O_3, SO_2, and NO_2

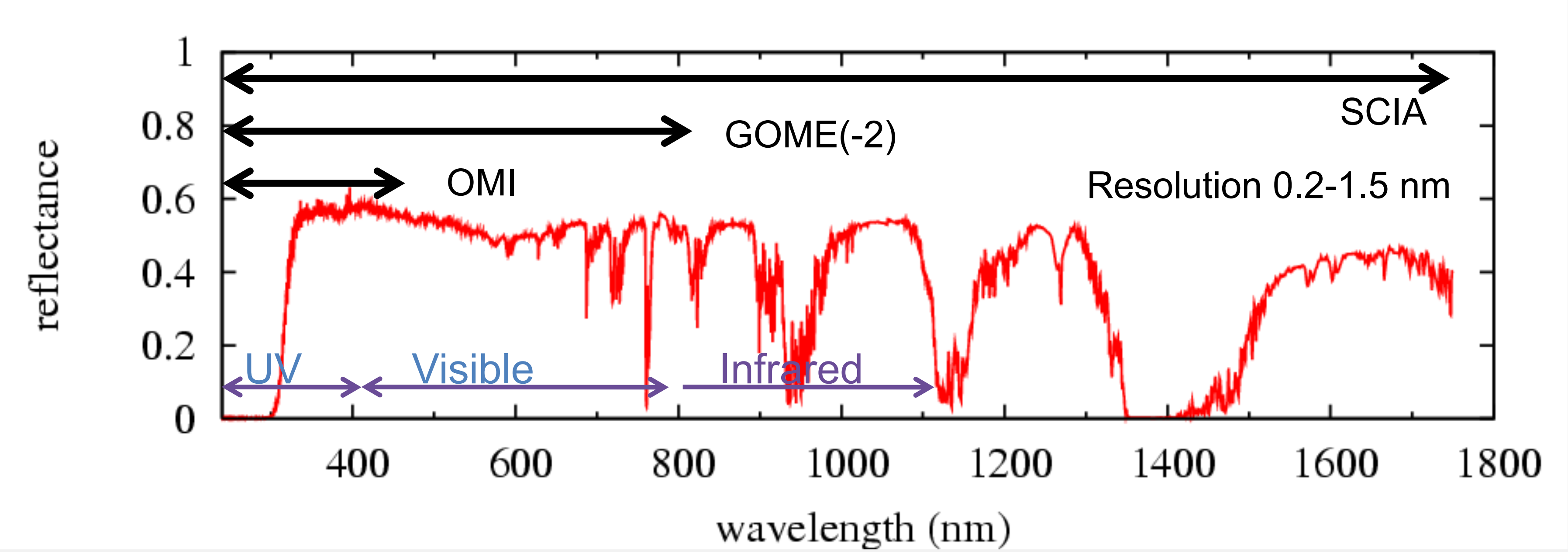
- Very little information can be obtained on the vertical distribution of trace gases
- Measurements at different wavelengths (technique of combining UV, visible, and IR measurements) provide some vertical information
  - penetration depth of photons increases with increasing wavelengths
  - Example: volcanic plumes of SO_2



Hyperspectral Instruments

Satellite UV-Visible Spectrometers

Instrument	Satellite	Wavelength
GOME	ERS-2	240 – 800 nm
SCIAMACHY	Envisat	240 – 1750 nm
OMI	EOS-Aura	270 – 500 nm
GOME-2	Metop-A	240 – 800 nm



Data Formats & Resolutions

Data Level	Description
Level 0	Raw data at full instrument resolution
Level 1A	Raw data, including radiometric and geometric calibration coefficients and geo-referencing parameters (e.g. platform ephemeris) computed and appended, but not applied to Level 0 data
Level 1B	Level 1A data that has been processed to sensor units (not all instruments have Level 1B source data)
Level 2	**Derived geophysical variables at the same resolution and location as Level 1 source data**
Level 2G & 3	**Variables mapped on uniform space-time grid scales, usually with some completeness and consistency**
Level 4	Model output or results from analyses of lower level data (e.g. variables derived from multiple measurements)

Spatial Resolution: Trace Gases

- Spatial resolution of current satellite instruments (10s of km diameter)
  – good enough to map tropospheric concentration fields on local to regional scales
  – fine enough to resolve individual power plants and large cities
- For species with short atmospheric lifetimes (e.g. NO_2), averaging over larger satellite pixels can lead to significant dilution of signals from point sources, complicating quantitative analysis and separation of emission sources
- For quantitative analysis: Level 2 and high resolution gridded Level 3 data are optimal

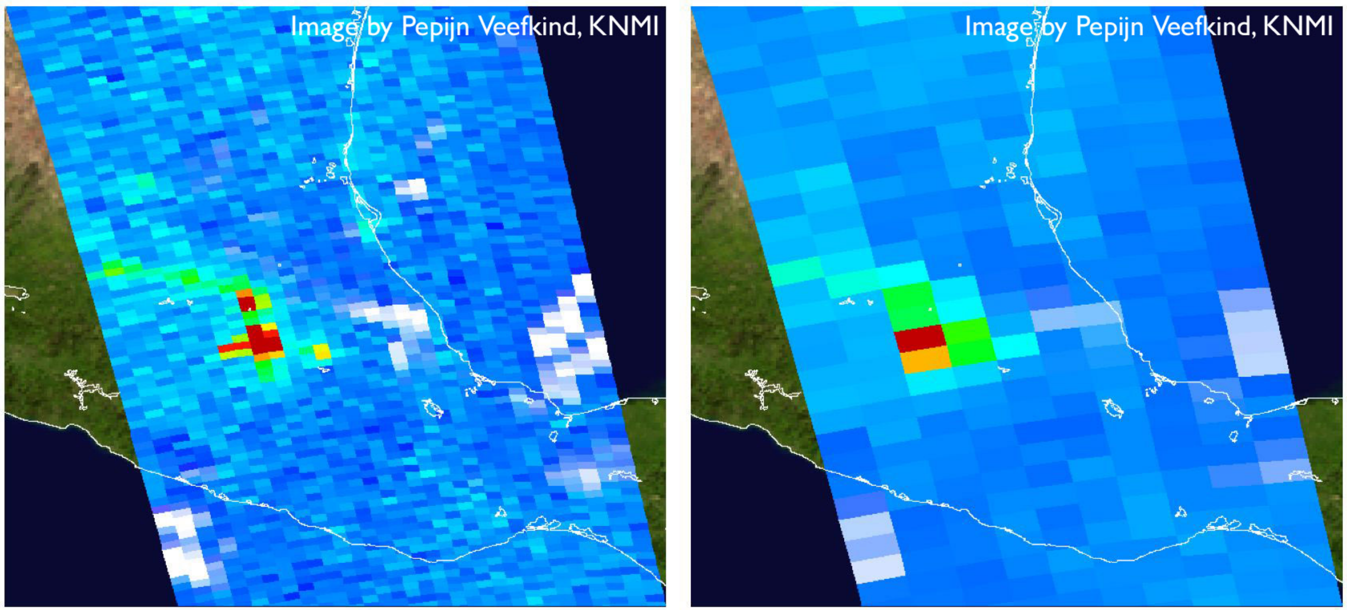
Source: Richter, 2010

Advantages of Using Level 3 vs. Level 2 Data

- Uniform grid
- One file per day
- Smaller sized files
- Quality flags and filtering criteria have been applied

Perspective…

Spatial Resolution



OMI 24x13 km^2

Approx. GOME-2 72x39 km^2

Mexico City, Jan. 20, 2005

Quantification of Gas Abundances

Satellite Tracer	Units
OMI O_3, SO_2	Dobson Units
OMI NO_2, Column Amounts (also AIRS and MOPITT CO)	Molecules/cm^2
AIRS and MOPITT CO Vertical Levels	Volume Mixing Ratio

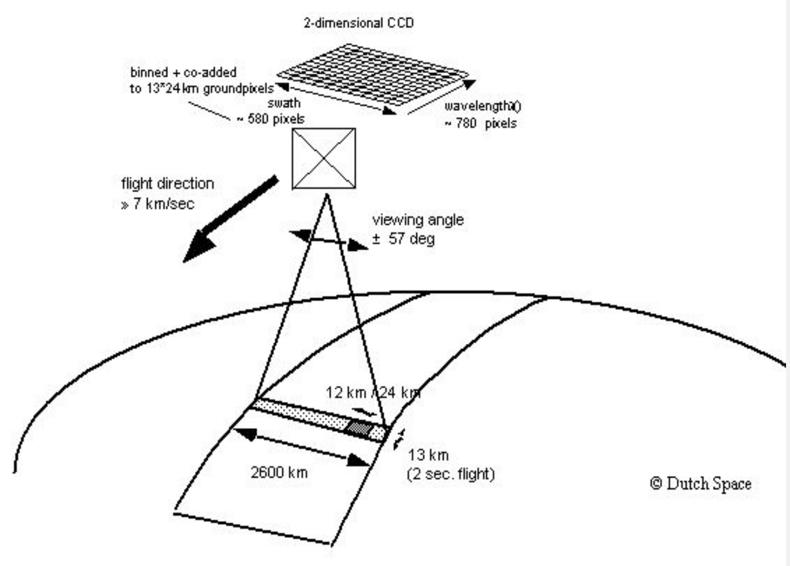
Ozone Measuring Instrument (OMI)

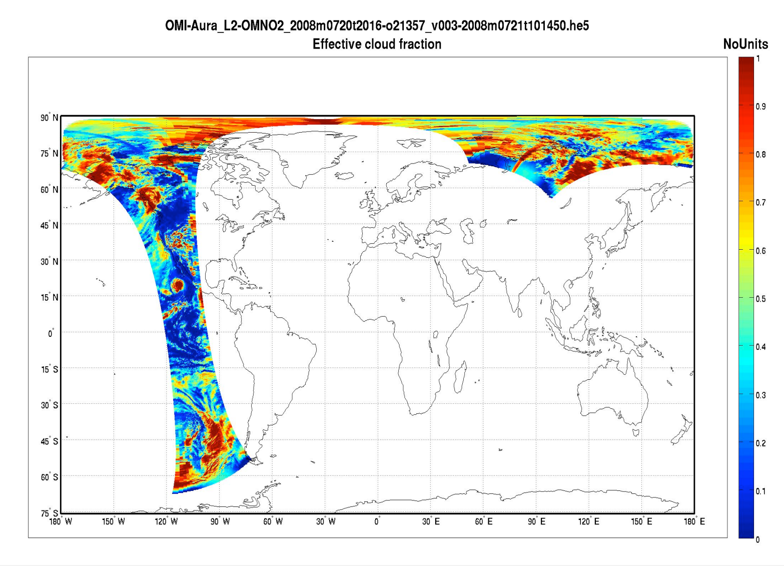
- Launched July 15, 2004
- NASA EOS Aura Satellite
- Nadir-viewing UV/Visible
  - 270 – 310 nm at 0.6 nm
  - 310 – 500 nm at 0.45 nm
- 1:40 p.m. equatorial crossing time
- 13x24 km^2 at nadir
- Daily global coverage

- Products
  - Total Column O_3
  - Tropospheric Column O_3 (experimental but not applicable in the mid-latitudes)
  - Aerosol optical depth (in UV)
  - Column Formaldehyde
  - Column NO_2
  - Column SO_2

Data Granule

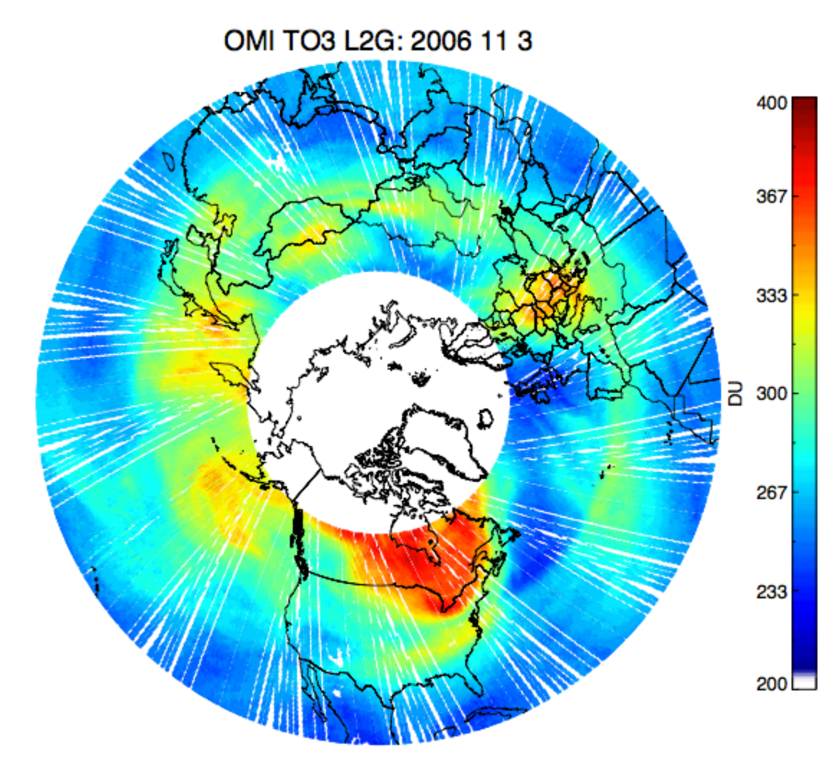
- Product File
  - covers sunlit portion of the orbit with an approx. 2,600 km wide swath
  - contains 60 binned pixels or scenes per viewing line
- 14 or 15 granules are produced daily, providing fully contiguous coverage of the globe

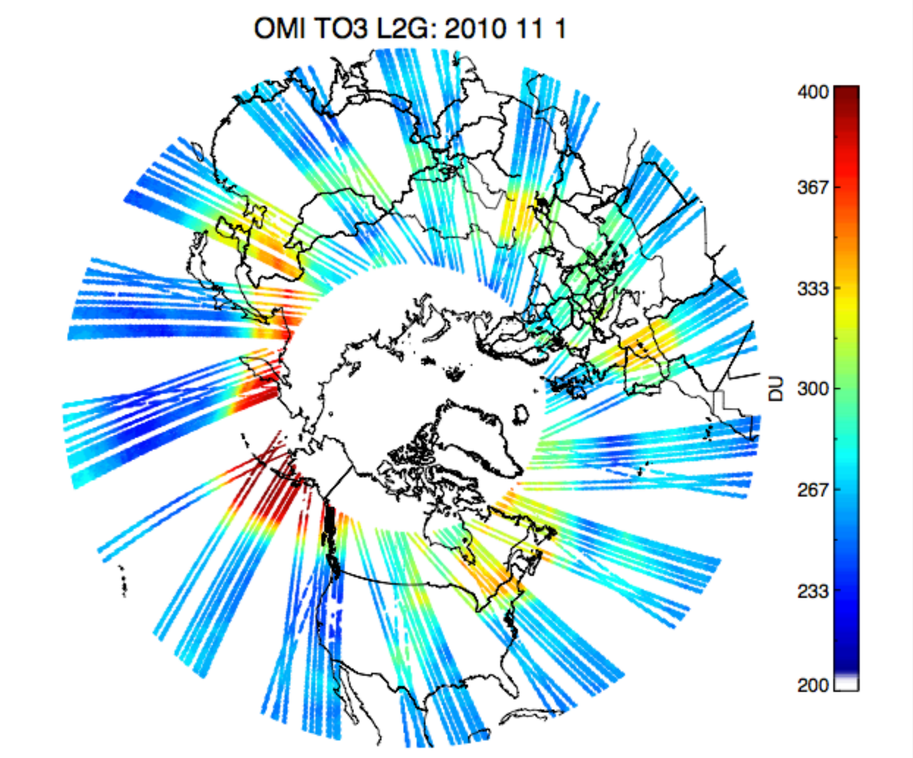




Important Information Regarding OMI

- Almost 50% data loss since 2008 (row anomaly effect)
- Affects O_3, SO_2, and to some extent NO_2 OMI products





OMI Ozone and Formaldehyde

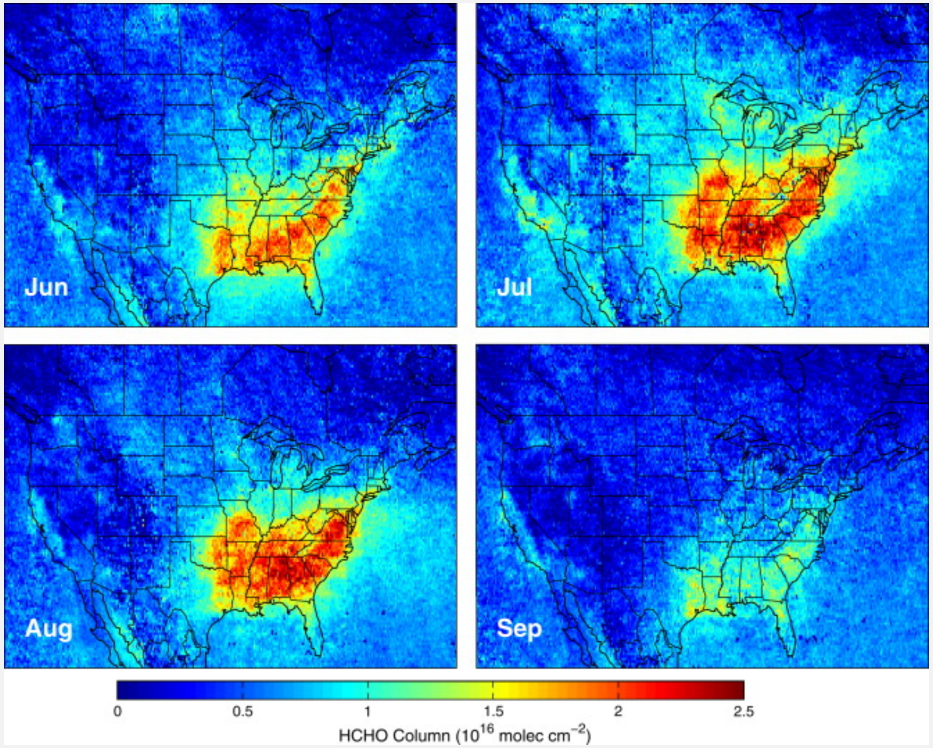
OMI Ozone in the Troposphere

- OMI is **not** sensitive to ozone near the surface
- There are tropospheric ozone products in development
  – they currently cannot be used for air quality monitoring
- Retrieval of boundary layer O_3 from satellite remote sensing remains a daunting task

OMI Formaldehyde (CH_2O)

- Data is reliable for 2004-2009 only
- Data re-processing is planned to account for the growing background noise and row anomalies

HCHO is a proxy for isoprene emissions

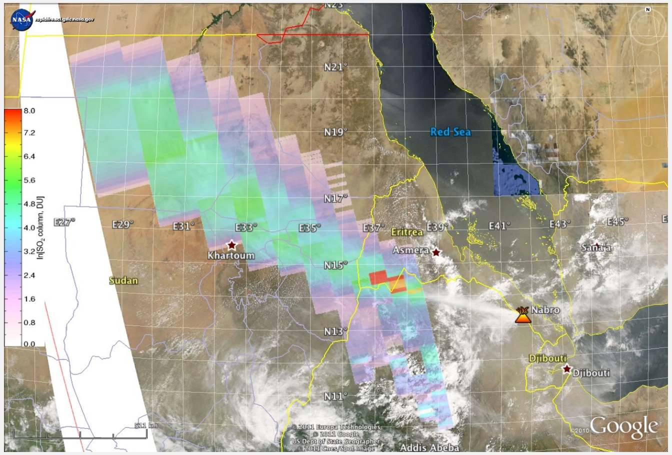


Source: Martin, Randall. Satellite remote sensing of surface air quality. Atmospheric Environment 42(34), 7823-7843, 2008.


Planetary Boundary Layer (PBL)
Volcanic SO_2
Tropospheric Column NO_2

OMI SO_2 in the Boundary Layer

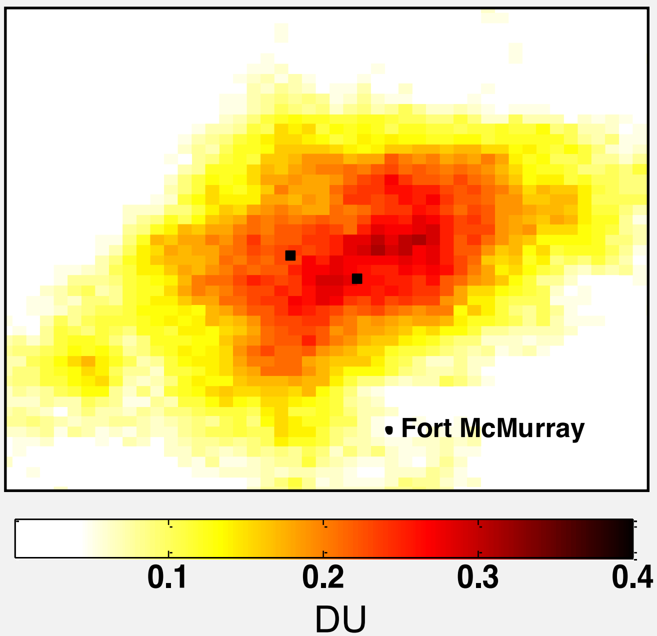
- Dataset Short Name = OMSO2e
  - Product Level: 3
  - Begin: October 1, 2004
  - Resolution: 0.25° lon x 0.25°lat
- Cloud-screened best measurement
  - Frequency: daily
  - Granule (File) Coverage: 15 orbits
  - File Size (approx): 5 mb



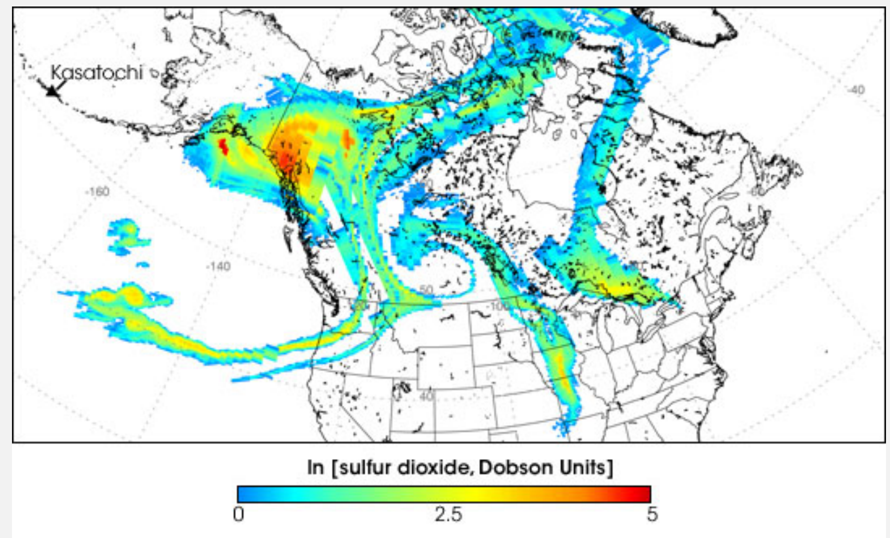
- Contains best pixel data, screened for OMI row anomaly, clouds, and other data quality flags
- Data: http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2e_v003.shtml

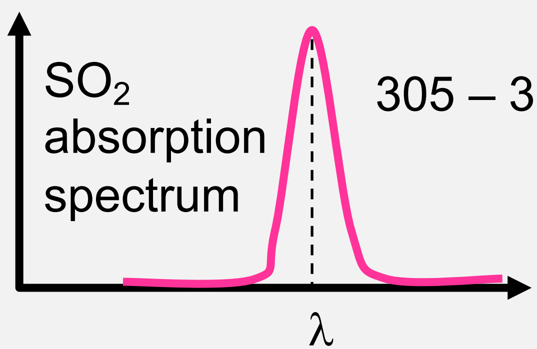
Perspective: What is Considered High SO_2?

2005-2010 Mean SO_2 Over Canadian Oil Sands



OMI SO_2 from Kasatochi Volcano August 8-12, 2008

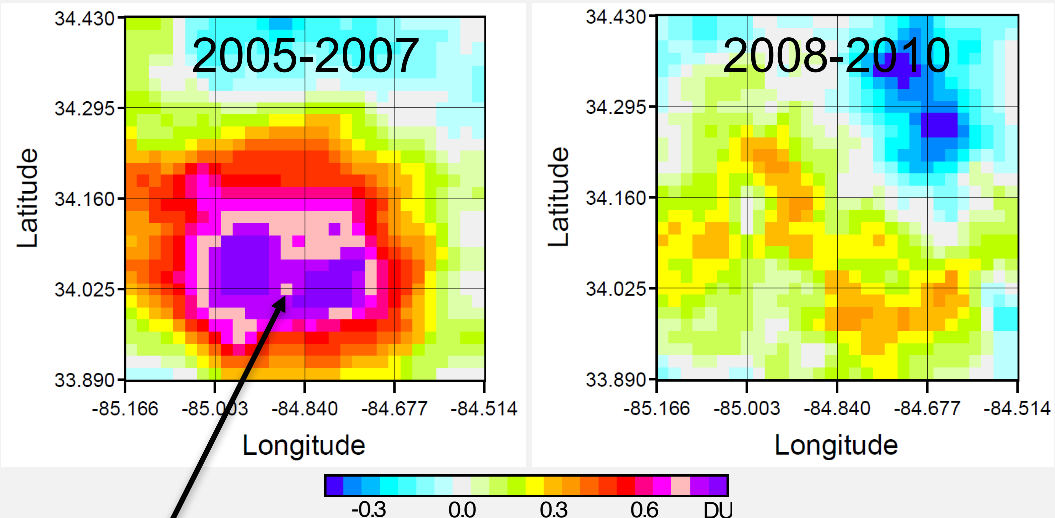


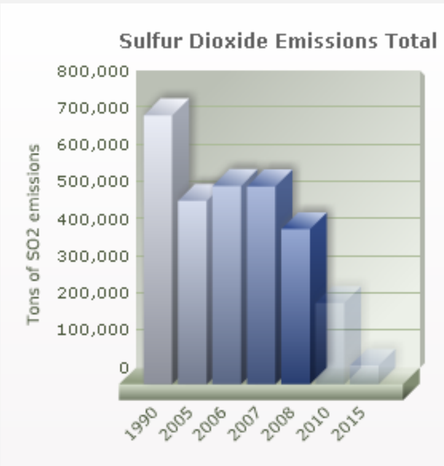


McLinden, C. A., et al. (2012), Air quality over the Canadian oil sands: A first assessment using satellite observations, Geophys. Res. Lett., 39, L04804, doi:10.1029/2011GL050273.

Perspective: What is considered high SO_2?

U.S. Source #1: Bowen Coal Power Plant, Georgia (3500 MW), SO_2 Emissions: 170 kT in 2006



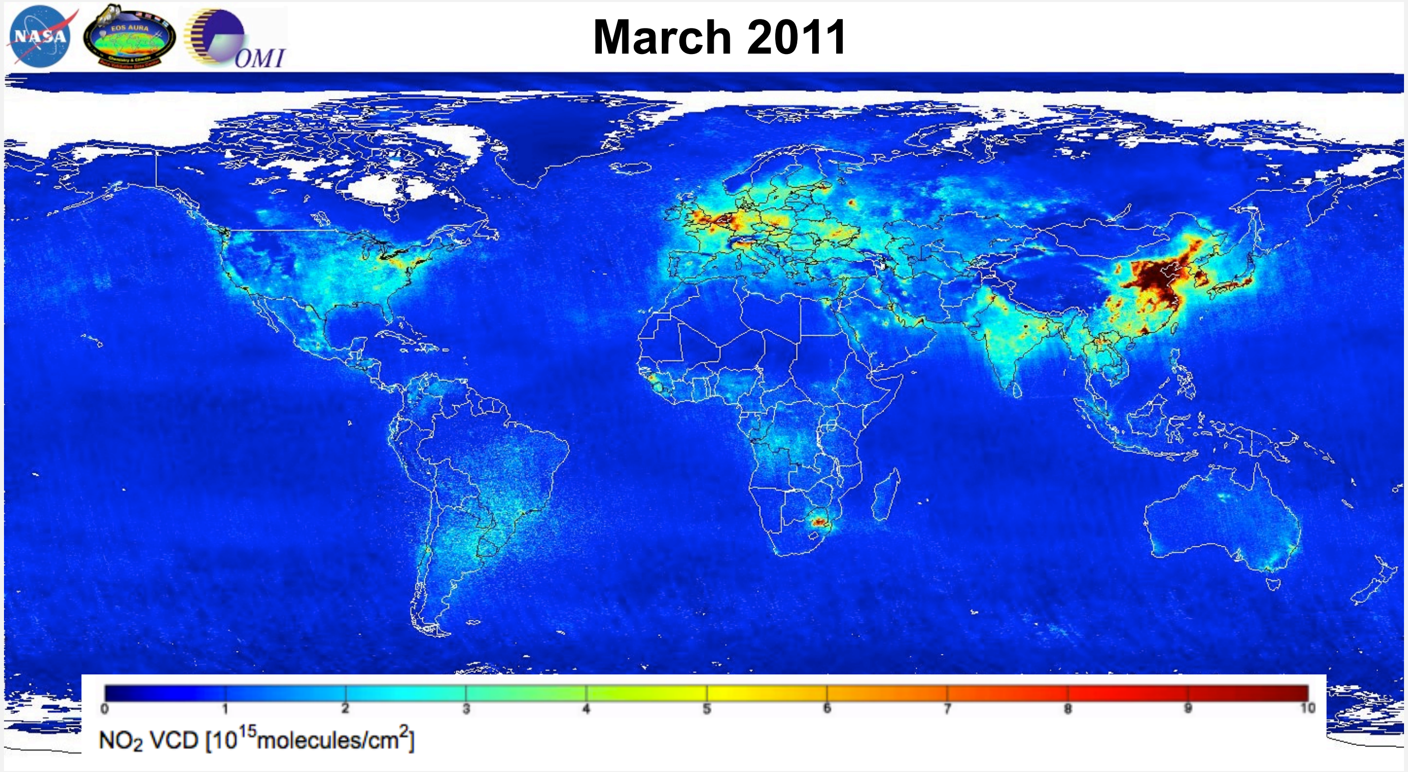


"In **2008**, the mammoth construction program yielded the first scrubbers, sophisticated equipment that will reduce our overall systems emissions by as much as 90 percent"

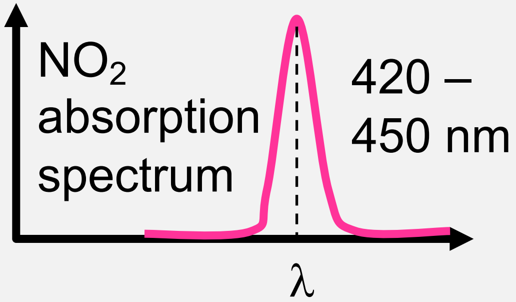
Georgia Power website

Source: V. Fioletov, et al., 2011

OMI NO_2



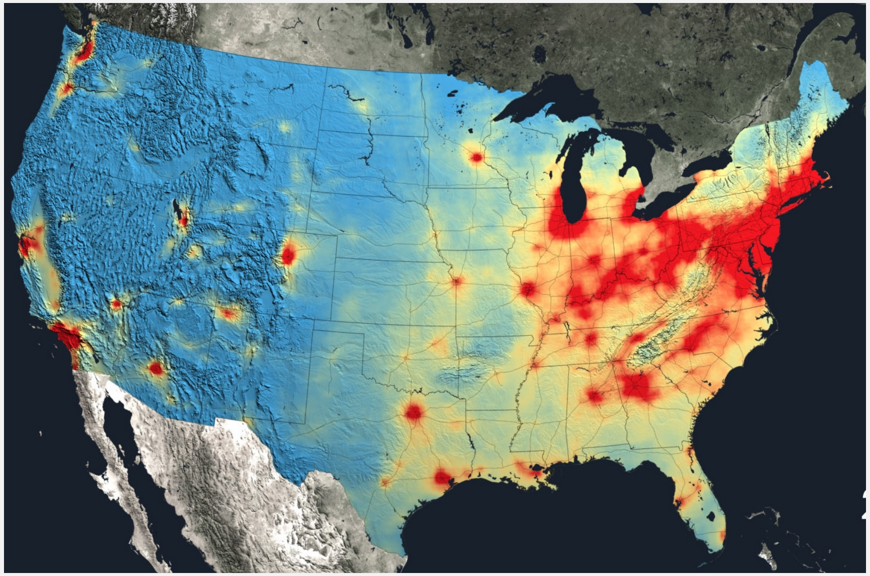
OMI
March 2011
0 1 2 3 4 5 6 7 8 9 10
NO_2 VCD [10^{15}molecules/cm^2]



NO_2 absorption spectrum
420 – 450 nm
λ

Nitrogen Dioxide (NO_2)

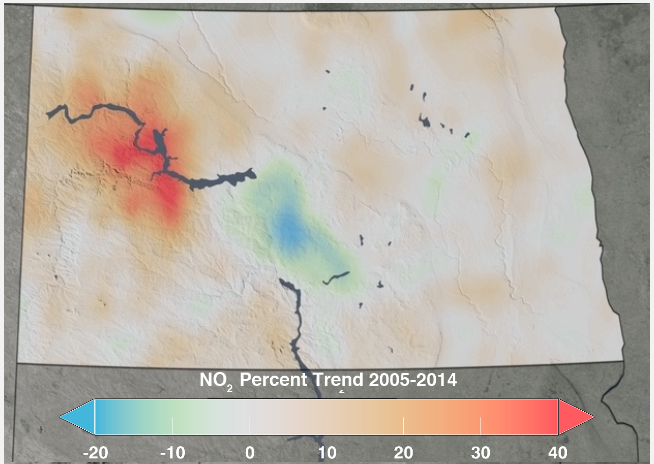
- NO_2 is produced when coal and gasoline are burned
  - comes out of tailpipes and smokestacks
- Unhealthy to breathe and correlated with morbidity and mortality
  - likely since it is emitted alongside air toxins & is a necessary ingredient for ozone formation



Source: Duncan, B.N. et al. (2016)

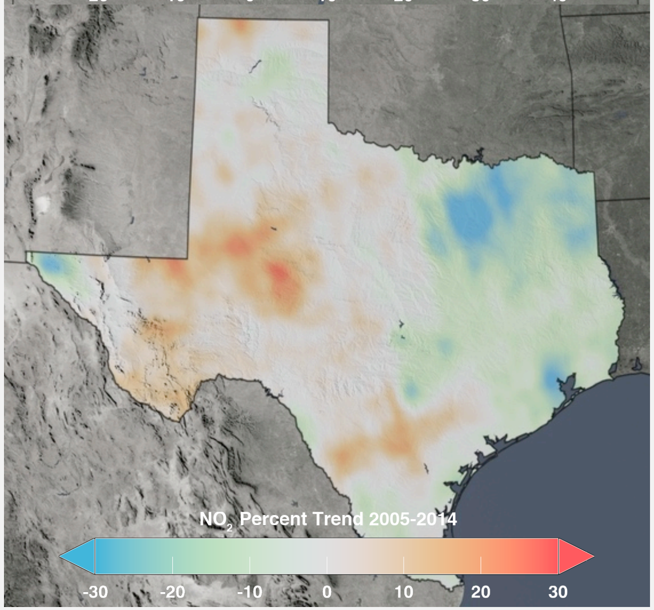
OMI Detects NO_2 Increases from ONG Activities

2005-2014

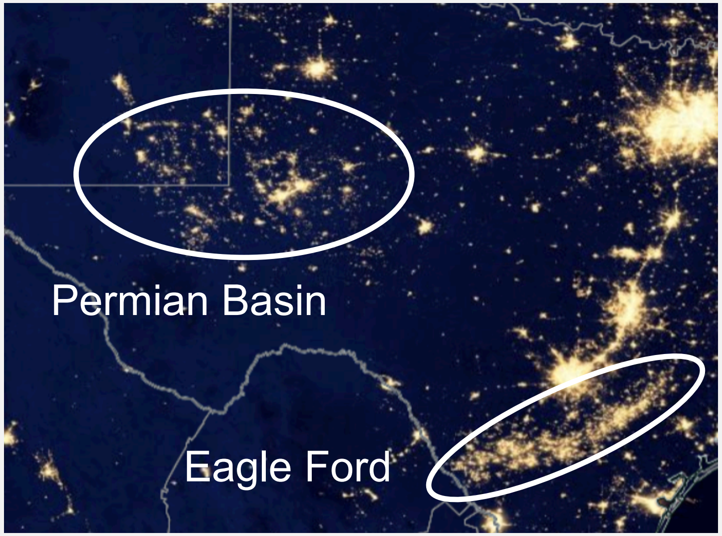


North Dakota

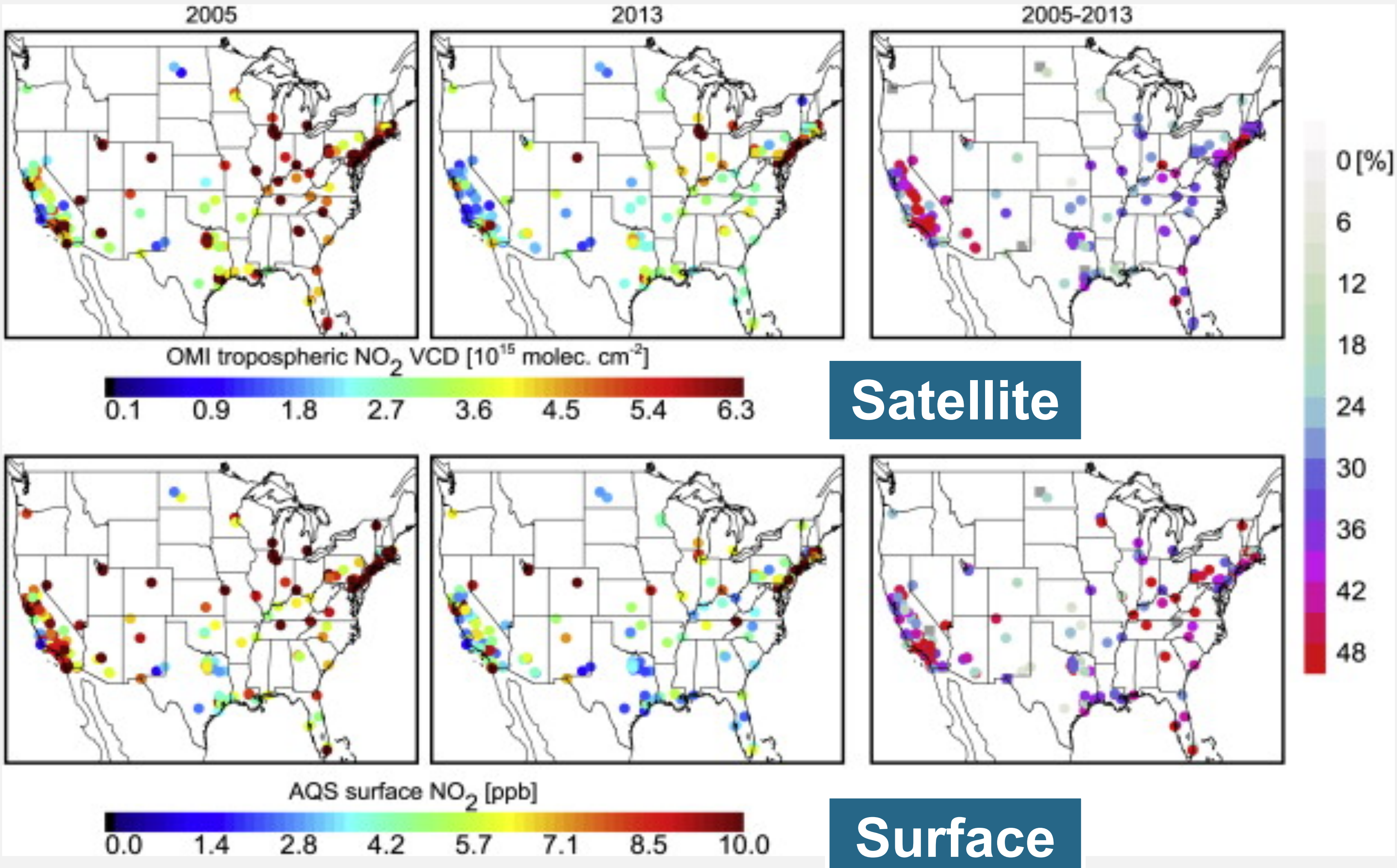
Suomi NPP VIIRS Lights at Night



Texas

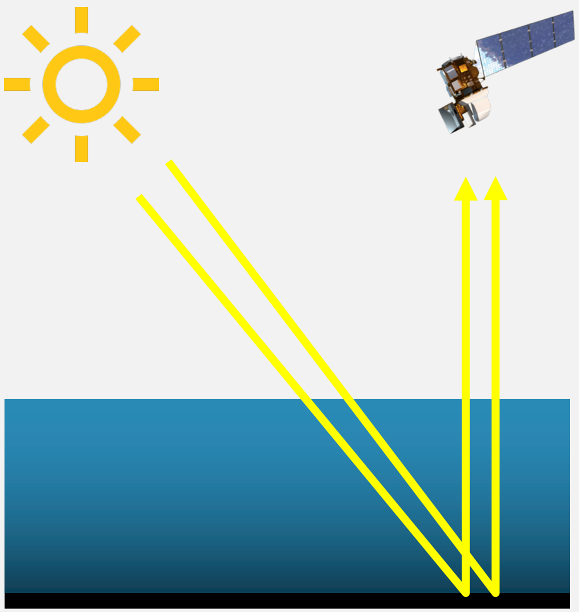


Satellite and AQS NO2 Trends



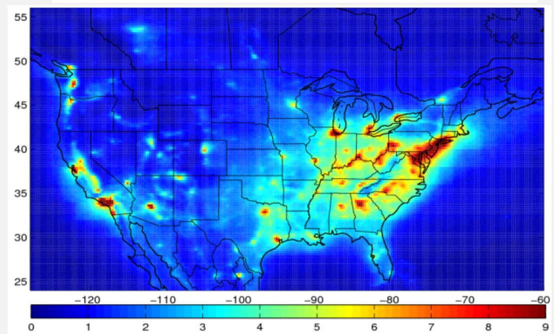
Source: Lamsal, L.N. et al. (2016)

Estimating Satellite Based Surface NO_2



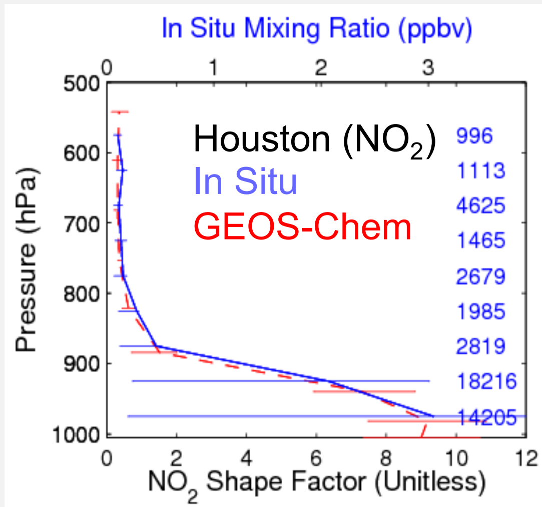
Scattering by Earth surface and atmosphere

NO_2 Column



$$S_O = \Omega_O \left[\frac{S_M}{\Omega_M} \right]$$

Model Profile

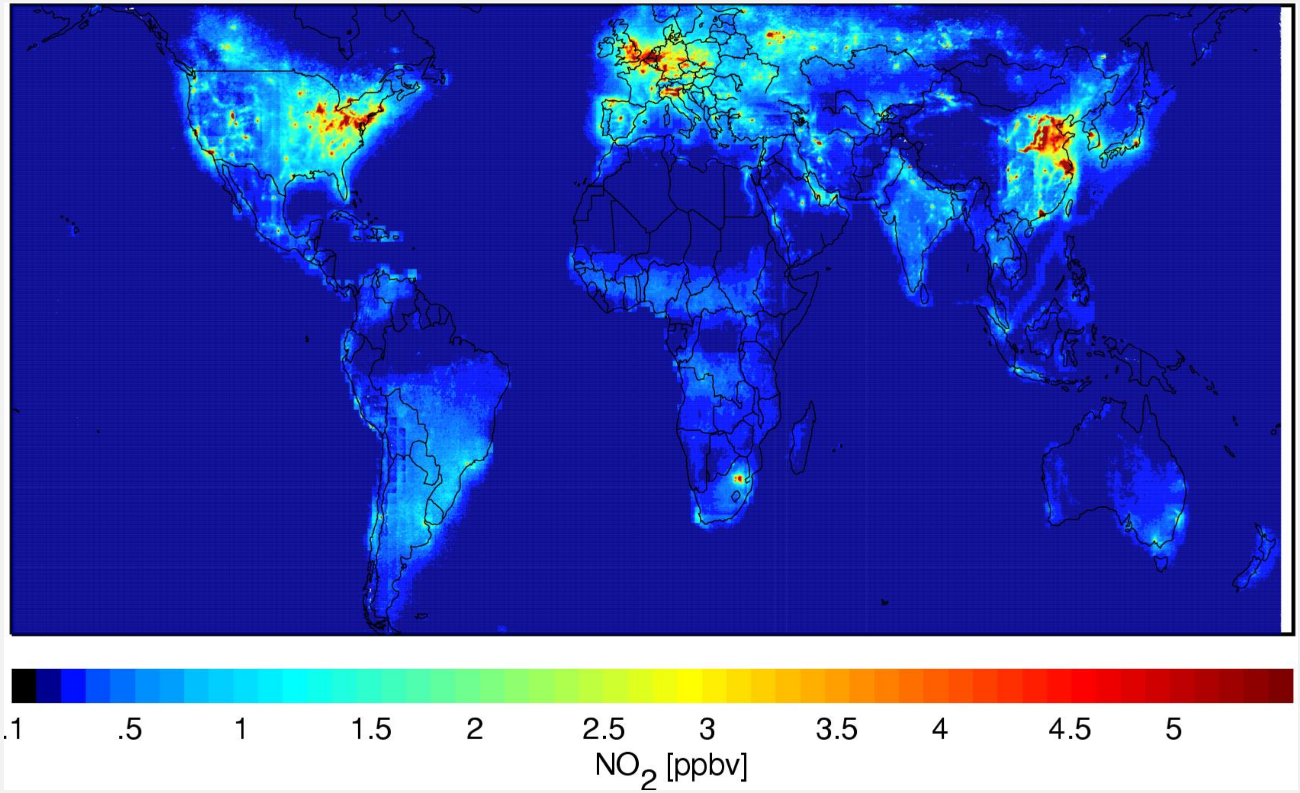


S → Surface Concentration

Ω → Tropospheric column

Courtesy of Randall Martin

Ground-Level Afternoon NO_2 Inferred from OMI for 2005



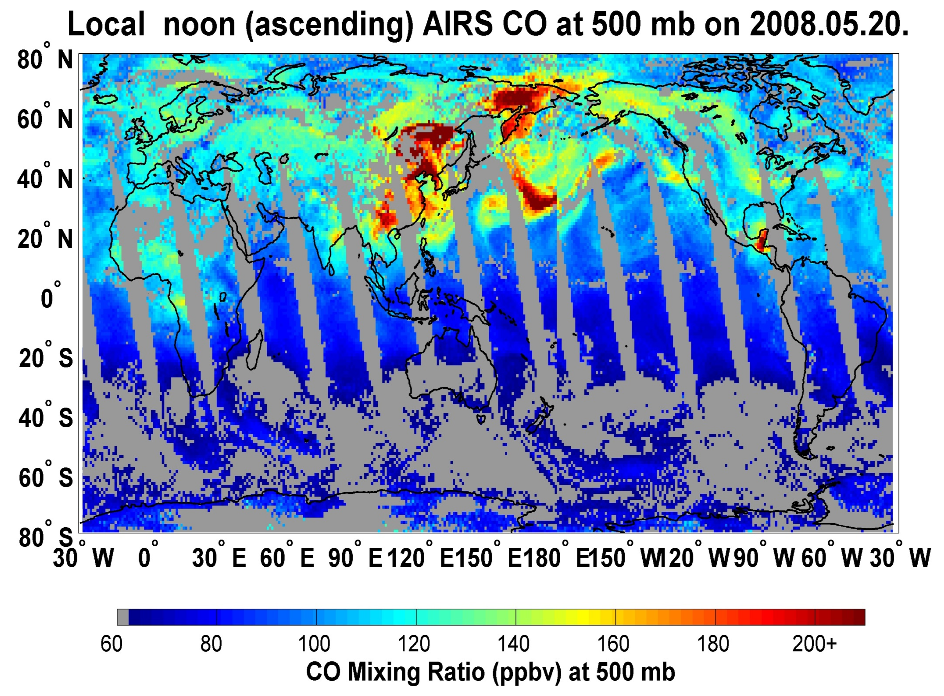
- Also available at: http://fizz.phys.dal.ca/~atmos/
- Note: this is a research product and not an official NASA product

Source: Lok Lamsal


More on OMI NO_2 Data & Applications:
airquality.gsfc.nasa.gov/

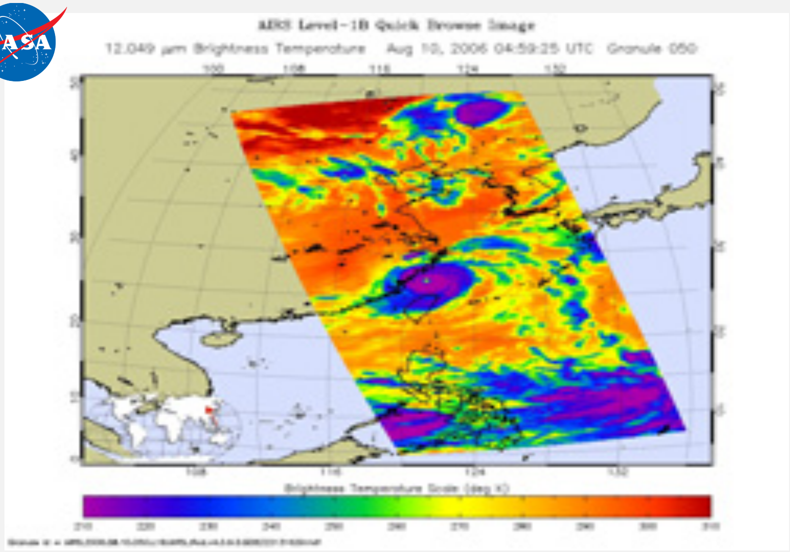
Carbon Monoxide

- Top Column Density
- Also sensitive to vertical distribution of CO
- Greatest sensitivity to CO variability is at 500 mb
- Mixing ratio can be larger away from the source

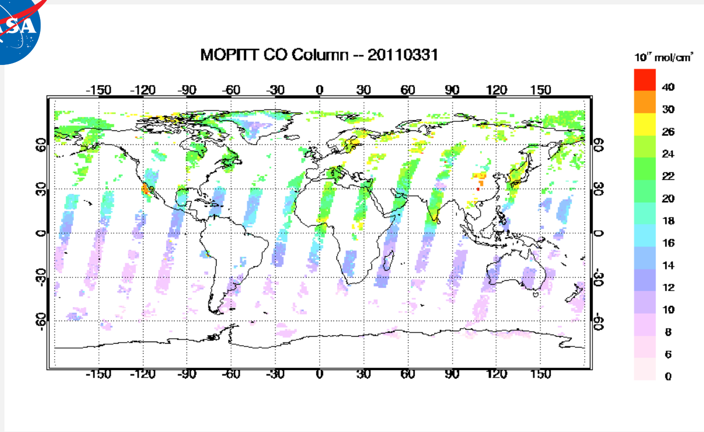


Current CO Sensors

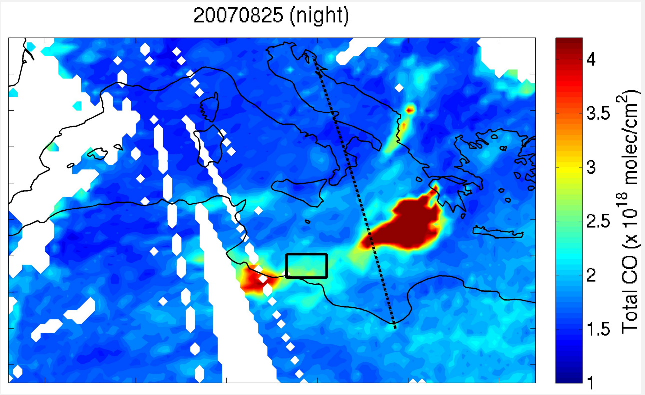
AIRS: Atmospheric Infrared Sounder



MOPITT: Measurements of Pollution in The Troposphere



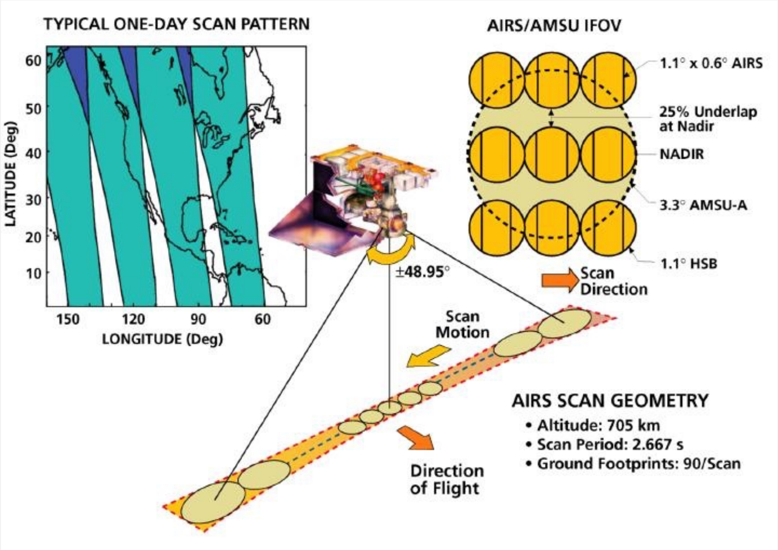
IASI: Infrared Atmospheric Sounding Interferometer



Atmospheric Infrared Sounder (AIRS)

http://airs.jpl.nasa.gov/

- Operational since Sep 2002
- Nadir sounding instrument
- Pixel size
  - 14 km at nadir
  - 41x21 km edges
- Swath Width: 1,650 km
- Equator Crossing Times
  - 1:30 (ascending)
  - 13:30 (descending)
- Column Measurements in molecules/cm^3



- Profile Measurements:
  - 9 vertical layers
  - 901.866 hPa – 0.16 hPa
- Data source: Level 2 pixel and Level 3 gridded 1°x1° resolution

AIRS

- Has excellent global coverage with ‘minor’ gaps – particularly over CONUS
- Can easily track biomass burning plumes
  - AIRS swath width is ~1650 km where MOPITT is 640 km
  - Twice daily coverage with AIRS (daytime and nighttime)
- Ascending Orbit = Daytime
- Descending Orbit = Nighttime

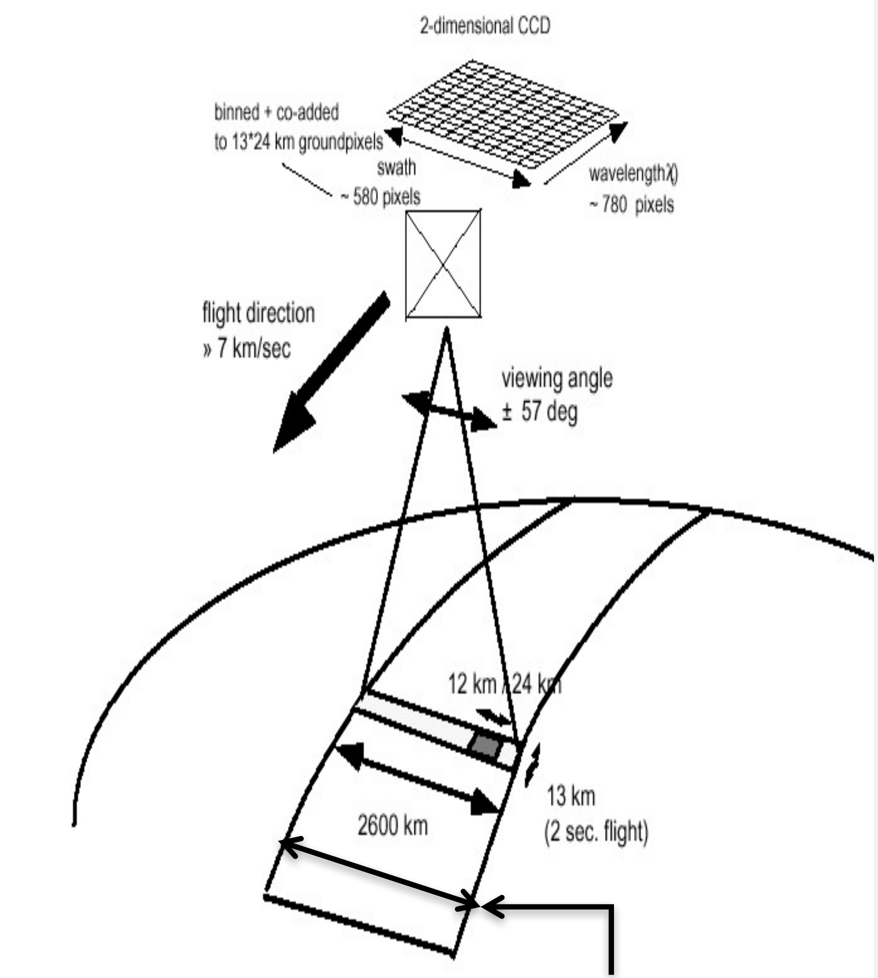
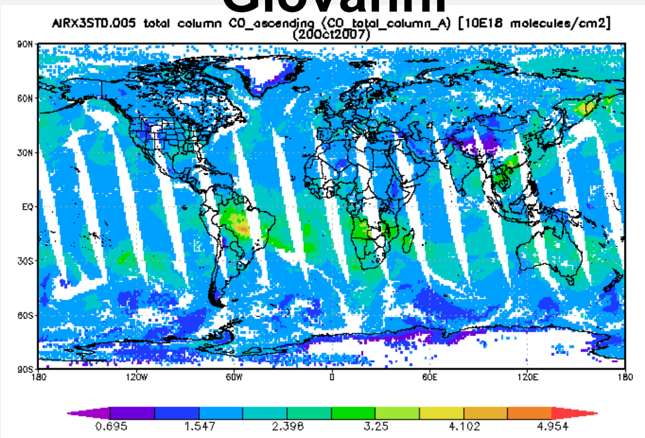


Figure 2.1 Measurement principle of OMI.

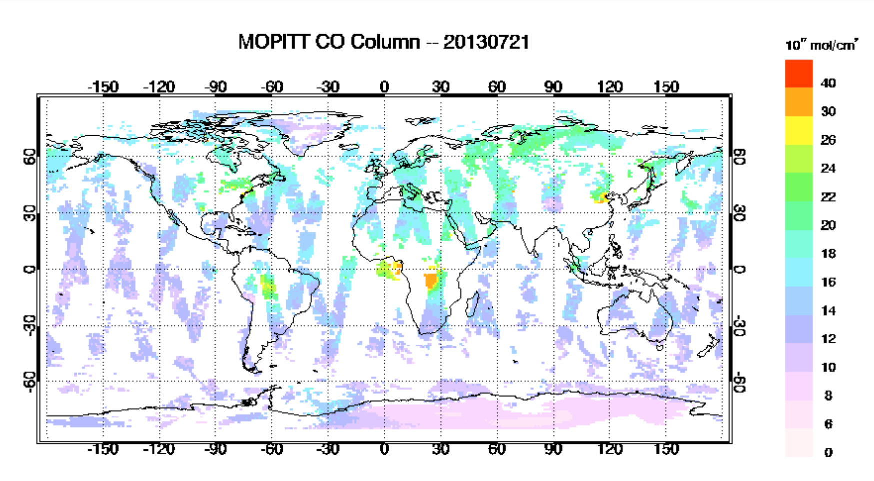
AIRS vs. MOPPITT CO

AIRS Level 2 from NRT Website

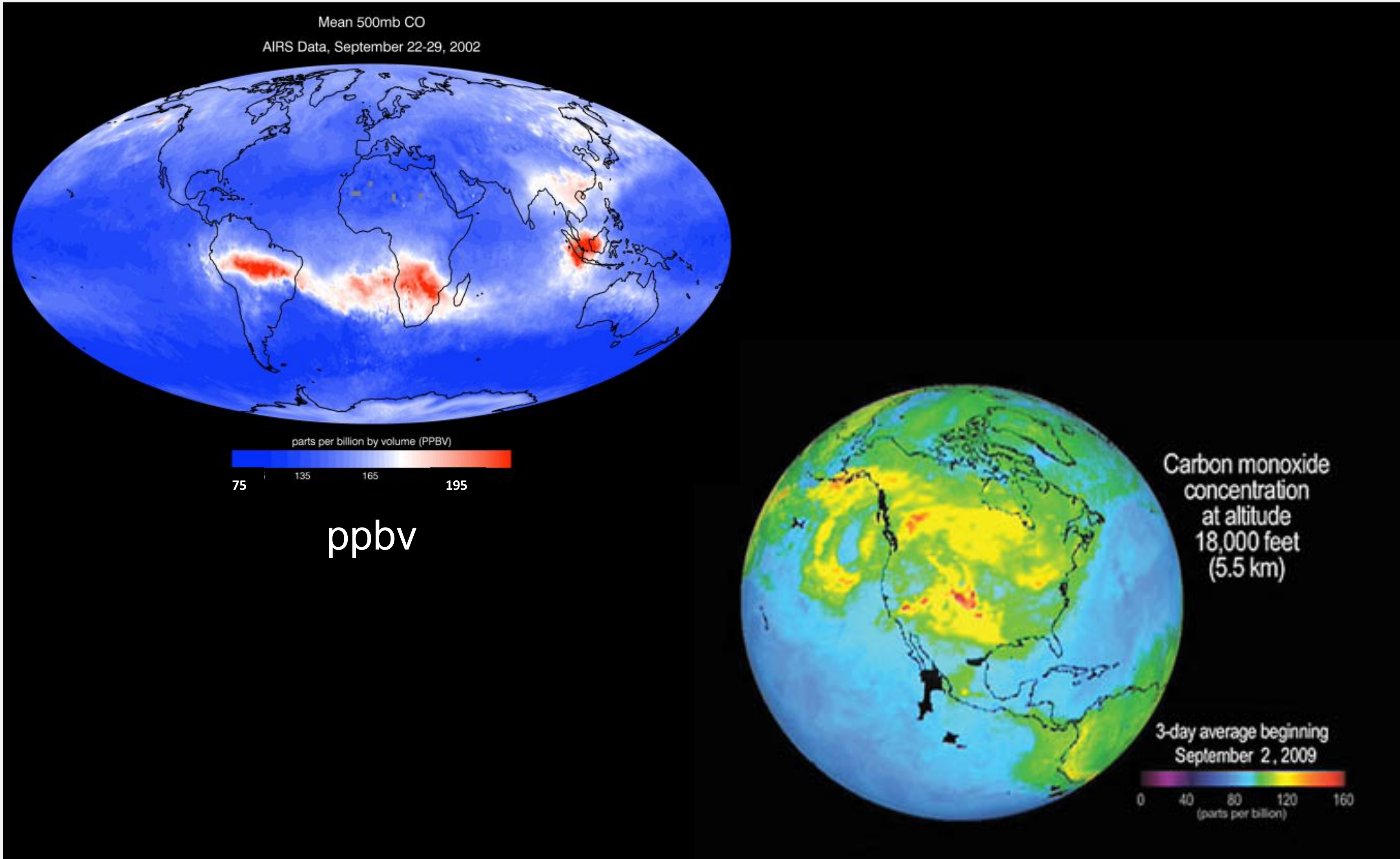
AIRS Level 3, 1° x1 ° from Giovanni



MOPPITT Level 3, 1° x1 °



Long Range Transport of CO



Data Product Summaries

OMI SO_2 Gridded Product Summary

SO_2 Product	Level	Data Short Name	Sensitivity	Use
PBL SO^2	L3 0.25° x0.25°	OMSO2e	0.6 km	Fossil fuel, industry
TRL SO^2	L2G 0.25° x0.25°	OMSO2G	3 km	Industry outflow
TRM SO^2	L2G 0.25° x0.25°	OMSO2G	5 km	Optimized for volcanic degassing
STL SO^2	L2G 0.25° x0.25°	OMSO2G	15 km	Explosive volcanic eruptions

Caveat: Unlike the OMSO2e 'best' product, L2G data is **not** screened for clouds, sza, quality flags, and row anomalies

Level 2 Pixel (Footprint) Size at Nadir

	AIRS	14 x 14 km
	MOPITT	22 x 22km
	TES	8.3 km 5.3 km
	SCIAMACHY	30 km 60 km
	IASI	12 x 12 km

Comparison Chart

	MOPITT	AIRS	TES	IASI	SCIAMACY
Product / Pixel size	22 x 22 km	14 x 14 km	5.3 x 8.3 km 100 m between pixels	50 km 12 x 12 km	30 x 60 km
Swath Width	650 km	1,650 km	N/A	2,200 km	1,000 km
Global Coverage / Repeat Cycle	3 day composite for global coverage	2x per day (day & night)	16 day repeat cycle	2x per day (day & night)	6 days
Overpass Time	10:30	13:30	2:30, 14:30	9:30, 21:30	10:00

Comparison Chart

	MOPITT	AIRS	TES	IASI	SCIAMACY
Product Resolution	L3 1° Grid	L3 1° Grid	L3 5 x 8 km	NO L3 Product	L3 0.5° Grid
Products Available	L2 L3, Daily, Monthly	L2 granule L3	L2 granule	L2 NOAA & ESA	2B-swath 3-global
Vertical Sensitivity	mid & lower troposphere	mid tropo-sphere	mid & lower troposphere	mid tropo-sphere	total column only
Product Accuracy	TIR: 10% Near Surface: 30%	10-20%	20%	<10%	10-20%

Comparison Chart

	MOPITT	AIRS	TES	IASI	SCIAMACY
Notes	• TIR and NIR channels	• QA flags in L2 and L3 • Next product will include near surface	• Report data for clouds • 0-25% • Simul-taneous trace gas	• 250 km sampling ESA • Should average to 4 x 5°	

Comparison Chart

	MOPITT	AIRS	TES	IASI	SCIAMACHY
Product/pixel size	22 x 22 Km	14 x 14 km	5.3 x 8.3 KM 100 M between pixels	50 KM 12 x 12 KM	30 x 60KM
Swath width	650 KM	1650 KM	N/A	2200 KM	1000 KM
Global Coverage/ Repeat Cycle	3 Days Composite for global coverage	2X per day (day and night)	16 days Repeat Cycle	2X per day (day and night)	6 Days
Overpass time	10:30 AM	13:30	2:30 AM / PM	9:30 AM/PM	10:00 AM
Product Resolution	L3 1 Degree grid	L3 1 Degree grid	L3 5x8km	NO L3 Product	L3 0.5 Degree grid
Products available	L2 L3 Daily, Monthly	Level 2 (granule) Level 3	L2 granule	L2 NOAA and ESA	2B - swath 3 - global
Vertical sensitivity	Mid and lower troposphere	Mid-Troposphere	mid and lower troposphere	mid troposphere	Total column only
Product accuracy	TIR - 10% Near Surface 30%	10 - 20%	20%	< 10%	10 - 20%
Other notes	TIR and NIR Channels	QA flags in L2 and L3	Report data for clouds 0 -25% Simultaneous trace gas	250 KM sampling ESA Should avg. to 4x5 deg.	